

PARTITIONING SOIL PHOSPHORUS INTO THREE DISCRETE POOLS OF DIFFERING AVAILABILITY¹

Fengmao Guo² and Russell S. Yost²

The Hedley phosphorus (P) fractionation procedure provides an alternative for characterizing soil P availability without qualifying the component P species. Interpretation of results involving all fractions is complicated and offers little practical utility. The objective of this study was to group P fractions of similar availability into three functional pools according to the plant availability of the P fractions. These grouped pools may simplify practical use of fractionation data and provide insights into differences in availability and cycling of added P in diverse soils. Eight soils in the greenhouse were treated with four levels of P and planted with 14 consecutive crops. Soils were fractionated using a modified Hedley method. The seven fractions were then grouped into three discrete pools of decreasing availability: the readily available, the reversibly available, and the sparingly available. Phosphorus extracted by the iron-impregnated filter paper strips (Strip P) and inorganic P extracted by 0.5 M NaHCO₃ (NaHCO₃-P_i) were readily available in all soils. The reversibly available P fractions differed between the slightly weathered and the highly weathered soils. In the slightly weathered soils, the reversibly available P included the organic P (P_o) (NaHCO₃- and NaOH-P_o), NaOH-P_i, HCl-P, and residual P. In the highly weathered soils, NaOH-P_i and organic P were considered reversibly available. No P fractions appeared to be sparingly available in the three slightly weathered soils. The residual P was the sparingly available P in the highly weathered soils. The results suggest quantitatively that P availability was greater when added to slightly weathered soils than when added to highly weathered soils. (Soil Science 1998;163:822-833)

Key words: Phosphorus, pools, fractionation, highly weathered soils.

QUANTIFYING the differences in availability and cycling of P added in diverse soils remains a difficult task. Although soil test methods (Kamprath and Watson 1980; Fixen and Grove 1990; McCollum 1991), fractionation procedures (Chang and Jackson 1957; Williams et al. 1971; Syers et al. 1972) and mechanistic approaches (Parfitt 1978; Barrow 1980; McLaughlin et al. 1981; Goldberg and Sposito 1985; Parfitt et al. 1989) have been attempted, reliable estimates of

available soil P have seldom been made using these approaches because of the complexity of the chemistry and mineralogy of soil P. Soil P availability exists as a continuum; unequivocal identification of P compounds or fractions is difficult.

An alternative approach, which divides the soil P continuum into fractions using extractants of differing strength and composition, was proposed by Hedley et al. (1982). The underlying assumption was that readily available soil P in the continuum is removed first with mild extractants, and the plant-unavailable P can only be extracted with strong acids and oxidizers. Hedley's procedure has been applied widely to the study of P fractions in both slightly weathered (Hedley et al. 1982; Tiessen et al. 1983; O'Halloran et al. 1987; Richards et al. 1995) and highly weathered soils

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(Agbenin and Tiessen 1994; Beck and Sanchez 1994; Schmidt et al. 1996). Phosphorus fraction changes caused by organic amendments have also been reported (Hedley et al. 1982; Leinweber 1996; Iyamuremye et al. 1996). These previous studies focused on revealing differences in the sizes of P fractions in soils receiving various treatments (Hedley et al. 1982; Richards et al. 1995; Schmidt et al. 1996; Leinweber 1996; Iyamuremye et al. 1996), with differing weathering intensity (Tiessen et al. 1984; Beck and Sanchez 1994), and under various cultural practices (Hedley et al. 1982; Tiessen et al. 1983; O'Halloran et al. 1987).

Although separating total P into seven fractions, as described in previous studies, helps to elucidate the differences in size of various P fractions, the P fractions could be of greater practical value should they be grouped into fewer functional pools of management implications. These pools can then be used to improve soil P management through approaches such as modeling (Russell 1977; Wolf et al. 1987) and decision aids (Yost et al. 1992). Grouping of P fractions of similar availability requires exhaustion experiments to verify the availability of the P fractions. However, such exhaustion experiments involving diverse soils are limited.

The objective of this study was to group the fractions into functional pools that can be assigned specific roles in P management. The availability of the P fractions in diverse soils was evaluated using an exhaustion experiment. A simplified scheme for grouping soil P into two dynamic pools, a labile (or available) pool and a stable (or unavailable) pool, has been used for modeling long-term crop response to fertilizer P (Wolf et al. 1987) and for evaluating residual

available P (Russell 1977). However, previous results (Guo et al. 1998) suggested that a large buffering pool exists to replenish the readily available P pool in both slightly and highly weathered soils. Therefore, in this study we quantified three functional pools: readily available, reversibly available, and sparingly available. The readily available pool represents P that is readily accessible by plant roots. The reversibly available P denotes the soil P reserve that is plant available when converted to readily available P. The sparingly available P is not available on a short time scale such as one or more crop cycles, but a small fraction of this pool may become available during long-term soil P transformations.

MATERIALS AND METHODS

Eight surface soils (0–15 cm) representing a wide range in weathering and P sorption capacity (Tables 1 and 2) were collected. Soil materials were air-dried and ground to pass a 4-mm sieve. Acidic soils were limed to pH 6.5 by adding laboratory grade powdered CaCO_3 . After liming, the soils were brought to their available water capacity (soil water between matrix potential of -0.03 and -1.5 MPa) and incubated for 4 weeks in plastic bags. Five-kilogram (dry basis) portions of each soil were weighed onto clean brown paper. The prescribed amount (Table 2) of P as $\text{Ca}(\text{H}_2\text{PO}_4)_2 \cdot \text{H}_2\text{O}$ was mixed thoroughly with each 5-kg soil portion. The soil materials were then placed in plastic pots (18 cm diam., 30 cm depth) and watered weekly with deionized water to available water capacity and allowed to dry in the greenhouse for a week. This wetting and drying incubation lasted for 4 weeks. Sixty days after P application, the following basal nu-

TABLE 1
Soil taxonomy and chemical properties

Soil series	Subgroup	pH (1:1 H_2O)	Organic carbon†	Carbonates	Total P‡
				(as CaCO_3)‡	
				g kg^{-1}	g kg^{-1}
Honouliuli	Typic Chromustert	7.26	16.6	3.2	1.840
Lualualei	Typic Chromustert	7.65	4.1	16.2	2.098
Nohili	Cumulic Haplaquoll	7.44	17.1	65.8	0.815
Paaloa	Rhodic Kandiodult	5.05	40.0	—	0.596
Wahiawa	Rhodic Eutrustox	5.05	35.8	—	0.528
Kapaa	Anionic Acrudox	4.92	45.6	—	1.722
Leilehua	Ustic Kanhaplohumult	4.66	44.0	—	0.699
Mahana	Humic Rhodic Haplustox	4.31	36.7	—	1.327

†Walkley and Black method (Nelson and Sommers 1982).

‡By the method of Nelson (1982).

§ Na_2CO_3 fusion (Olsen and Sommers 1982).

¶Negligible.

TABLE 2

Phosphorus application rates for the greenhouse experiment

Soil series	P applied to attain target solution P levels (mg L ⁻¹)†			
	Control	0.2	0.5	1.0
	mg P kg ⁻¹			
Low P sorption				
Honouliuli, Lualualei, and Nohili	0	100	250	500
Medium P sorption				
Paaloa, and Wahiawa	0	500	650	800
High P sorption				
Kapaa, Leilehua, Mahana	0	1400	1800	2200

†Determined by the Fox and Kamprath method (1970).

trients, including 50 mg N kg⁻¹ as urea, 60 mg K kg⁻¹ as KCl, 25 mg kg⁻¹ Mg as MgSO₄ · 7H₂O, and 5 mg kg⁻¹ Zn as ZnSO₄ · 7H₂O, were added to each pot and mixed. The experimental design was a randomized complete block with three replicates.

Corn (*Zea mays* L.) was grown in the pots for crops 1 to 10, 13, and 14. Crops 11 and 12 were planted with soybean [*Glycine max* (L.) Merr.]. Each pot of corn received 12 pregerminated seeds (Hybrid X304CF15, courtesy of Pioneer Hi-Bred International, Inc., Johnston, IA), which were placed 1 to 2 cm below the soil surface. Three days after emergence (DAE), each pot was thinned to 10 seedlings. Two additional doses of N at 50 mg kg⁻¹ were applied at 10 and 20 DAE. Plants were allowed to grow for 4 weeks. For the two soybean crops, five healthy, noninoculated, and presoaked seeds were placed 1 to 2 cm below the soil surface in each pot and thinned to 3 seedlings per pot 3 DAE. Nitrogen was applied at 56 mg kg⁻¹ and split equally between 0 and 15 DAE. Boron (as sodium borate) and molybdenum (as ammonium molybdate) were both applied at 0.9 mg kg⁻¹ in the first soybean crop. Other supplemental nutrients were added in amounts similar to those of corn. Soybean plants were grown for 45 days. The pots were watered daily with deionized H₂O, and moisture was maintained near soil-available water capacity throughout the growth period.

At harvest, plants were cut at the soil surface, washed with deionized H₂O, dried at 70°C, and ground to pass a 0.5-mm sieve. Soil in each pot was crushed and mixed, and the fine roots were incorporated in the same manner as that of Fixen and Ludwick (1982).

Phosphorus in tissue was determined with the following procedure: A 0.050–0.100-g sample was ashed at 500°C for 4 h and dissolved in 1.0 mL 1 M HCl, which was then diluted to 10 mL. Solution P was determined by the Murphy and Riley method (1962).

A 2-g soil sample was collected from each pot after harvests 0, 2, 4, 6, 8, 10, 12, and 14. Samples were air-dried and ground to pass a 0.25-mm sieve and were then extracted sequentially for P using a Hedley procedure (Hedley et al. 1982) with modifications that are described below. Triplicate 0.5000-g samples of soil were weighed into 40-mL screw-capped centrifuge tubes, 30.0 mL of extractant was added, and the tubes were shaken for 45 min of each hour for 16 h. The extractants, in sequential order, were: (i) 30 mL deionized water and one 2 × 10-cm Fe-impregnated strip as prepared according to Guo et al. (1996); (ii) 0.5 M NaHCO₃ at pH 8.5; (iii) 0.1 M NaOH; (iv) 1 M HCl; and (v) 5.0 mL conc. H₂SO₄ (ca. 18 M) and 2 to 3 mL H₂O₂ (ca. 30%) in 0.5-mL increments. Inorganic P (P_i) in the extracts was determined by the method of Murphy and Riley (1962) after pH adjustment using β-nitrophenol as an indicator. Total P (P_T) was also measured in both the NaHCO₃ and the NaOH extracts for calculating organic P (P_o). P_T was determined with the Murphy and Riley (1962) method after autoclave digestion to convert P_o to P_i with acid ammonium peroxysulfate as described in the Standard Methods (APHA, AWWA, and WEF 1995). P_o was calculated as the difference between P_T and P_i in the extracts. Data were analyzed using SAS for Windows, V 6.11. (SAS 1996). The procedures for calculating the correlation coefficients were described where these coefficients appeared.

RESULTS AND DISCUSSION

Evaluation of the Availability of Phosphorus Fractions

Available soil P was estimated by continuous P withdrawal by the 14 crops in the greenhouse. Relationships between changes in selected P fractions and accumulated plant P uptake in soils added with P to raise solution P to 0.2 mg L⁻¹ are shown in Figs. 1 to 3. The scale of the x-axis of the figures was purposely plotted from high to low. An approximately diagonal line suggests uniform plant availability of P fractions across the observed range of the various P fractions; a relatively flat curve indicates a fast decline of the fraction, and the buffering pool for the P fraction at that range was small; a vertical curve indicates

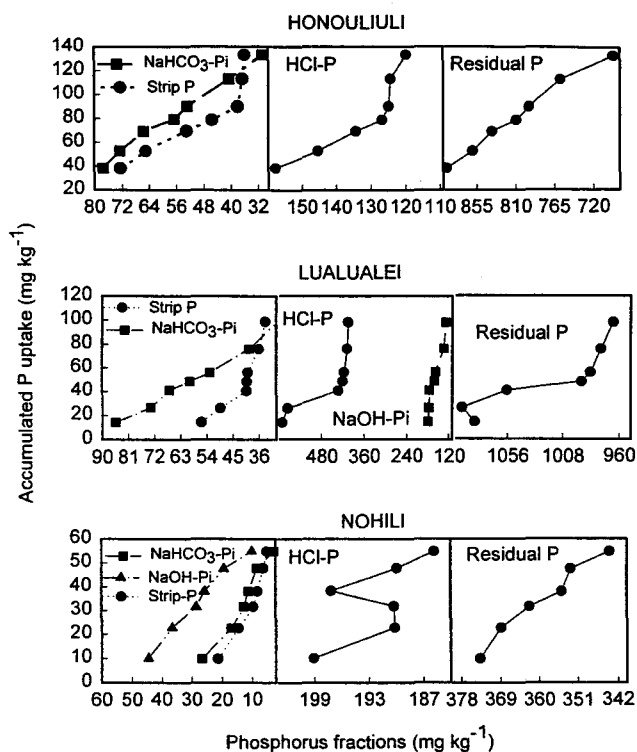


Fig. 1. Relationships between accumulated plant P uptake and changes in P fractions in the slightly weathered soils. Phosphorus was added to raise soil solution P to 0.2 mg L⁻¹.

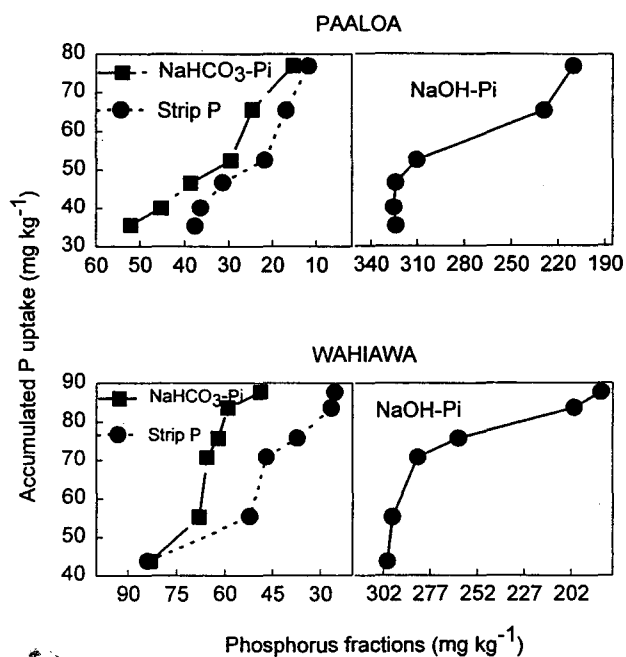


Fig. 2. Relationships between accumulated plant P uptake and changes in P fractions in the two highly weathered soils of medium P sorption. Phosphorus was added to raise soil solution P to 0.2 mg L⁻¹.

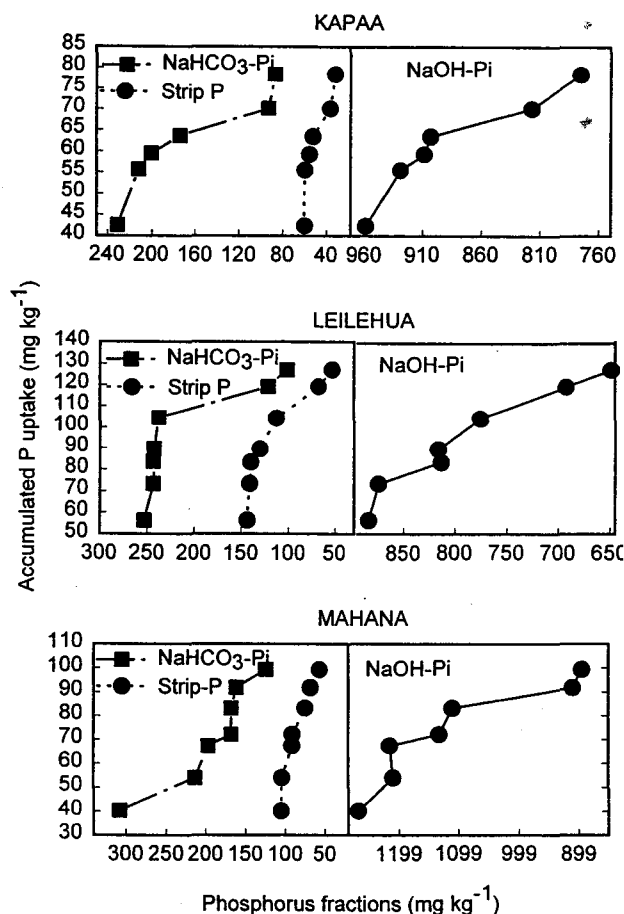


Fig. 3. Relationships between accumulated plant P uptake and changes in P fractions in the three highly weathered soils of high P sorption. Phosphorus was added to raise soil solution P to 0.2 mg L⁻¹.

that the fraction was highly buffered, perhaps as a result of contributions from other P fractions in the soil.

In the slightly weathered soils, four P fractions—Strip P, NaHCO₃-P_i, HCl-P, and residual P—seemed to contribute most to available P because they declined as accumulated plant P increased (Fig. 1). In the Lualualei and the Nohili soils, NaOH-P_i also appeared to decline with accumulated P. In the slightly weathered soils, Strip P and NaHCO₃-P_i seemed to have similar availability until extractable P decreased to a certain level (40 mg kg⁻¹ in the Honouliuli and the Lualualei soils and 7 mg kg⁻¹ in the Nohili soil), as shown by their similar slopes of decline (Fig. 1). Continued plant P withdrawal did not lower Strip P much further, indicating that other fractions were replenishing the Strip P, which comprises primarily P bound to the reactive surfaces

that are in direct contact with the aqueous phase (Hingston et al. 1974) or as “more physically adsorbed phosphate” (Sharpley 1991). The compensatory fractions were the NaHCO₃-P_i, HCl-P, and residual P (Fig. 1). The residual P in all three slightly weathered soils declined as soil-available P was continuously removed. This occurred most in the Lualualei soil, which contained considerable calcite (Guo et al. 1998).

In the highly weathered soils, three fractions seemed to be responsive to plant P removal (Fig. 2). As in the slightly weathered soils, Strip P and NaHCO₃-P_i were the first fractions that were depleted by plants, and their relative contributions to plant available P could not be resolved (Figs. 2 and 3). The NaOH-P_i in the highly weathered soils was important in buffering available P supply in the highly weathered soils of this study. Strip P, NaHCO₃-P_i, and NaOH-P_i

seemed to be linked. When Strip P and $\text{NaHCO}_3\text{-P}_i$ were high, the decline in NaOH-P_i was slow in all five highly weathered soils; when Strip P and $\text{NaHCO}_3\text{-P}_i$ were somewhat exhausted, NaOH-P_i seemed to mobilize and replenish the Strip P and $\text{NaHCO}_3\text{-P}_i$ fractions. This was suggested by the rapid decline in NaOH-P_i when the decline in Strip P and $\text{NaHCO}_3\text{-P}_i$ became less (Figs. 2 and 3). Relationships between P fractions in soils and accumulated plant P uptake at the other P application rates were similar to those with P added to raise solution P to 0.2 mg L^{-1} and are not shown.

Correlation coefficients between P fractions measured after every other harvest and the corre-

sponding accumulated P uptake were calculated for each soil at each P level (Table 3). A significant negative coefficient indicates that the decline of a P fraction is correlated significantly to the increase in accumulated P uptake. For the six soils with low native soil P, the coefficients for the control (without P application) were not calculated because P fractions in those soils did not change as a result of low plant P removal. The decline of Strip P and $\text{NaHCO}_3\text{-P}_i$ was correlated highly with accumulated plant P removal in all soils at nearly all P levels (Table 3). The decline in NaOH-P_i in all soils except the Honouliuli soil was also correlated significantly with accumulated plant P uptake.

TABLE 3
Pearson correlation coefficients between P fractions measured after every other harvest and the corresponding accumulated plant P uptake†

Soils	Strip P_i	NaHCO_3		NaOH		HCl-P	Residual
		P_i	P_o	P_i	P_o		
Honouliuli							
0‡	-0.923	-0.995	—§	—	-0.863*	-0.823*	-0.914
100	-0.920	-0.997	—	—	-0.823*	-0.901	-0.994
250	-0.965	-0.985	—	—	-0.810*	-0.812*	-0.887
500	-0.918	-0.998	—	—	—	-0.811*	-0.994
Lualualei							
0	-0.929	-0.993	—	-0.987	—	-0.861*	-0.969
100	-0.915	-0.994	—	-0.970	—	-0.807*	-0.888
250	-0.944	-0.990	—	-0.930	—	-0.866	-0.939
500	-0.988	-0.994	—	-0.946	—	-0.784*	-0.976
Nohili							
100	-0.967	-0.982	—	-0.993	—	—	-0.983
250	-0.966	-0.969	—	-0.988	—	—	-0.985
500	-0.879	-0.986	—	-0.978	—	-0.802	-0.960
Paaloa							
500	-0.976	-0.980	-0.877*	-0.945	—	—	—
650	-0.971	-0.969	-0.951	-0.936	—	—	—
800	-0.986	-0.988	—	-0.771*	—	—	—
Wahiawa							
500	-0.961	-0.944	—	-0.895*	—	—	—
650	-0.983	-0.963	—	-0.923	—	—	—
800	-0.993	-0.981	—	-0.866*	—	—	—
Kapaa							
1400	-0.905*	-0.921	-0.865*	-0.944	—	—	—
1800	-0.908	-0.965	-0.940	-0.940	-0.775*	—	—
2200	-0.904	-0.892	-0.897	-0.997	—	—	—
Leilehua							
1400	-0.926	-0.851*	-0.605*	-0.970	—	—	—
1800	-0.958	-0.962	—	-0.958	—	—	—
2200	-0.897	-0.956	—	-0.991	—	—	—
Mahana							
1400	-0.964	-0.930	-0.893	-0.919	—	—	—
1800	-0.805*	-0.926	—	-0.860*	—	—	—
2200	-0.972	-0.910	-0.818	-0.866	—	—	—

†Correlations with $P < 0.01$ unless otherwise indicated by an *, which indicates $P < 0.05$.

‡Amounts of phosphorus applied in mg P kg^{-1} soil.

§Not significantly correlated.

In the slightly weathered soils, the decrease in HCl-P and residual P was correlated significantly with accumulated P uptake, which differed from that in the highly weathered soils (Table 3). The HCl-P in the slightly weathered soils may be mostly Ca-P (Williams et al. 1971). The residual P in the slightly weathered soils may also contain much Ca-P. The Ca-P formed with added P in the slightly weathered soils seemed to be more soluble than apatite, which is generally low in plant availability at high pH (Tiessen et al. 1984; Richards et al. 1995). Thus, the Ca-P extracted by HCl and in the residual P seemed to contribute to plant available P in the slightly weathered soils, presumably by compensating for the loss of Strip P and $\text{NaHCO}_3\text{-P}_i$. Previous workers (Hedley et al. 1982; Ivarsson 1990; McKenzie et al. 1992) reported similar changes in HCl-P and residual P during plant P removal.

In the highly weathered soils, NaOH-P_i seemed to buffer Strip P and $\text{NaHCO}_3\text{-P}_i$, and to function similarly to HCl-P and residual P in the slightly weathered soils. However, a significant correlation between Strip P, $\text{NaHCO}_3\text{-P}_i$, and NaOH-P_i and accumulated plant P does not indicate conclusively that Strip P, $\text{NaHCO}_3\text{-P}_i$, and NaOH-P_i contribute significantly to plant available P unless there is no accumulation of P fractions. In the slightly weathered soils, no accumulation of any fraction was observed; thus, a significant correlation does indicate the effect of plant P removal on the fractions. In the highly weathered soils, the decline in Strip P, $\text{NaHCO}_3\text{-P}_i$, and NaOH-P_i could also be attributed to a transformation to residual P, which increased while available P was being removed from the soils.

In an attempt to explore if the decline in Strip P, $\text{NaHCO}_3\text{-P}_i$, and NaOH-P_i in the highly weathered soils was attributable to plant P re-

moval, an alternative analysis was made. The correlations between P fraction decline measured after every two consecutive harvests and P uptake during the corresponding two harvests were calculated for all soils at all P rates. A significant coefficient would suggest that a large decline of a P fraction corresponds to a large P uptake during a two-crop period, and vice versa.

This analysis indicated that the decline in Strip P and $\text{NaHCO}_3\text{-P}_i$ was most probably caused by plant P removal because most coefficients were significant (Table 4). Whether the decline in NaOH-P_i was caused by transformation to residual P or to Strip P and $\text{NaHCO}_3\text{-P}_i$, which are subsequently available to plants, could not be determined by this study. This is a difficulty in identifying the mechanism of the decline in P fractions. Phosphorus fractions may decline as a result of plant P removal or because of chemical and physical processes. Previous work using path analysis (Tiessen et al. 1984; Beck and Sanchez 1994) was also unable to overcome this interpretational difficulty. Beck and Sanchez (1994) used path analysis results to suggest that NaOH-P_i contributed to plant availability on an Ultisol, possibly through equilibration with the resin-Pi (similar to Strip P in this study). Results of this study (Figs. 2 and 3) suggested that a reduced decline in Strip P and $\text{NaHCO}_3\text{-P}_i$ corresponded with a faster decline in NaOH-P_i in all highly weathered soils. Such correspondence may suggest that NaOH-P_i acted as a buffer of the Strip P and $\text{NaHCO}_3\text{-P}_i$ when they were depleted in the highly weathered soils.

Partition of P Pools

Phosphorus pools are concepts that are widely adopted but poorly defined. Unequivocal P pools have not and may never be determined.

TABLE 4
Pearson correlation coefficients[†] between P changes and plant P uptake during the period in which fraction changes occurred

Soils	Strip-P	NaHCO_3		NaOH		HCl-P	Residual
		Pi	Po	Pi	Po		
Honouliuli	0.853	—*	0.617	—	—	0.650	—
Lualualei	0.574	0.715	—	0.389*	—	—	—
Nohili	—	0.596	—	—	—	—	—
Paaloa	0.976	0.883	—	—	0.783	—	—
Wahiawa	0.934	0.697	—	—	0.883	—	—
Kapaa	0.874	0.411*	—	—	—	0.608	—
Leilehua	0.851	0.577	—	—	—	—	—
Mahana	0.868	—	—	—	—	—	—

[†]Correlations with $P < 0.01$ unless otherwise indicated by an *, which indicates $P < 0.05$.

*Not significantly correlated.

Arbitrary division is necessary because of the continuity in available soil P. Three general pools—readily available, intermediately available, and unavailable—have been used widely in the literature although various terms have often been used for the same pool. In this study, we suggest a scheme to partition the soil P continuum into three discrete pools for future inclusion of fractionation results into management systems. A simplified representation of the three functional pools and their interrelations is shown in Fig. 4.

The readily available P pool is the first removed by plant roots in the soil P continuum. It comprises primarily P bound to the reactive surfaces that are in direct contact with the aqueous phase (Hingston et al. 1974) or as “more physically adsorbed phosphate” (Sharpley 1991). The size of this pool determines the rate of P diffusion to plant roots and is the most sensitive to plant P removal of soil solution P. The Strip P and the $\text{NaHCO}_3\text{-P}_i$ are considered readily available in all soils.

The reversibly available P pool is probably the result of dissolution of P from secondary P compounds such as Ca-P in the slightly weathered soils, P from interior sites inside sesquioxide aggregates (Lookman et al. 1995), P associated with the amorphous Fe and Al oxides (Hedley et al. 1982; Tiessen et al. 1984; Wager et al. 1986), or mineralizable organic P. The organic P fractions ($\text{NaHCO}_3\text{-}$ and NaOH-P_o) separated by the Hedley's procedure were variable. The decline in $\text{NaHCO}_3\text{-}$ and NaOH-P_o was generally not correlated significantly with accumulated P or P uptake (Tables 3 and 4), but organic P appeared to fluctuate with microbial activity (data not shown). Both $\text{NaHCO}_3\text{-}$ and NaOH-P_o are thus considered reversibly available. In the slightly

weathered soils, the reversibly available P also included the HCl-P , NaOH-P_i , and residual P because none of them remained unchanged during plant P withdrawal (Fig. 1). The lack of accumulation in these fractions and the significant correlations between decline in these P fractions and accumulated P uptake indicated that they contribute to available P (Table 3). In the highly weathered soils, the NaOH-P_i declined as the available soil P was continuously removed from the soils (Figs. 2 and 3). It appeared to act as a buffer for the Strip P and $\text{NaHCO}_3\text{-P}_i$. Other workers also considered NaOH-P_i moderately labile and thought it would contribute to plant-available P (Tiessen et al. 1984; Ivarsson 1990). Thus, the NaOH-P_i was considered reversibly available in the highly weathered soils. The HCl-P in the highly weathered soils was generally negligible and appeared to decline with cropping (data not shown). Therefore, the HCl-P was also considered reversibly available P in the highly weathered soils.

We believe that absolutely plant-unavailable P does not exist during long-term P transformations, although some P fractions in the soil P continuum appear irreversible on a short time scale. The term sparingly available P is thus used to describe P that is plant inaccessible during a crop cycle. In the slightly weathered soils, no irreversible P was found, and no accumulation of P fractions was observed (Fig. 1). Therefore, these soils do not appear to have sparingly available P. Although Hedley's procedure separates a residual P fraction in the slightly weathered soils, the residual P appeared to be plant available even when the readily available P was considerable (Fig. 1). Other workers have also provided evidence that residual P is plant available in the slightly weathered soils (Hedley et al. 1982; McKenzie et al. 1992). If part of Hedley's residual P is indeed sparingly available in the slightly weathered soils, then the procedure failed to quantify this fraction. In the highly weathered soils, the residual P failed to respond to continuous plant P removal and gradually accumulated (Fig. 5). Thus, the residual P in these soils belongs to the sparingly available pool. Accumulation of residual P in highly weathered soils during plant removal of P has not been previously reported. Previous work lacked either the time to observe the changes after P application or a high P level that allows for exhaustive cropping without requiring additional P.

Using the proposed grouping, the sizes of the pools in the eight soils and their relative percentages of the total P were calculated (Table 5).

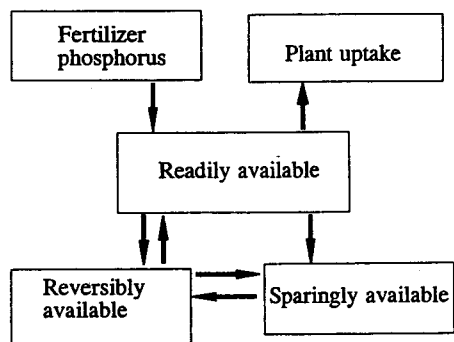


Fig. 4. A simplified representation of the three functional P pools and their interrelationships

Availability of added P was greater in the slightly weathered soils than in the highly weathered soils. This was indicated by a greater amount of reversibly available P, which is potentially more plant available, in the slightly weathered soils than in the highly weathered soils (Table 5). Thus, in the greenhouse, when both groups of soils were fertilized to the same soil solution P levels, the slightly weathered soils sustained plant growth longer than the highly weathered soils (results

not shown). The sparingly available pool ranged from 30 to 50% of the total P in the highly weathered soils (Table 5). Thus, recovery of added P in the highly weathered soils was generally low.

A large variation in P pools was found in soils of similar P sorption capacity. For example, sorption curves of the Paaloa and the Wahiawa soils were similar, but added P was more available in the Wahiawa than in the Paaloa soil, as indicated

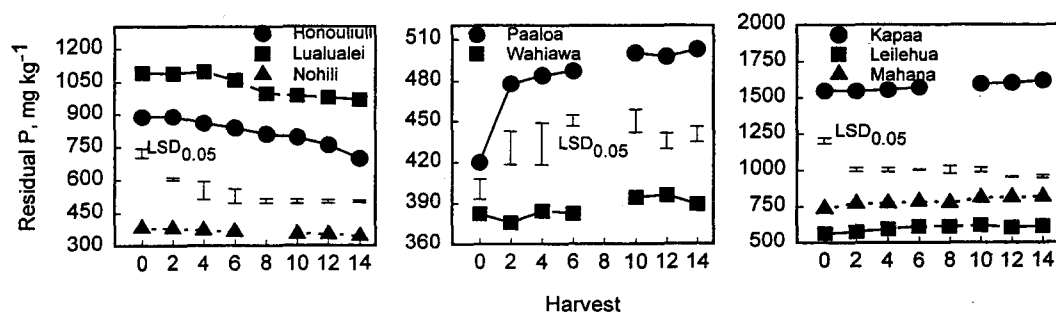


Fig. 5. Changes in residual P in eight soils under exhaustive cropping. Phosphorus was added to raise soil solution P to 0.2 mg L⁻¹.

TABLE 5
Functional P pools in 8 soils with varying amounts of P added

Soils	Readily available		Reversibly available		Sparingly available	
	mg kg ⁻¹	%†	mg kg	%	mg kg	%
<i>Slightly weathered soils</i>						
Honouliuli						
100‡	172.5	10.8	1425.1	89.2	—§	—
500	435.5	21.7	1568.5	78.3	—	—
Lualualei						
100	207.5	9.1	2068.2	90.9	—	—
500	390.5	14.3	2337.1	85.7	—	—
Nohili						
100	62.8	8.3	697.6	91.7	—	—
500	298.2	24.1	937.2	75.9	—	—
<i>Highly weathered soils</i>						
Paaloa						
500	185.5	18.9	370.5	38.0	419.4	43.0
Wahiawa						
500	273.1	27.5	333.7	34.0	382.0	38.5
Kapaa						
1400	509.5	16.9	959.8	31.9	1540.0	48.8
Leilehua						
1400	616.3	30.3	851.2	41.9	564.5	27.8
Mahana						
1400	583.6	23.2	1193.8	47.5	735.4	29.3

†Expressed as percentage the total soil P, which was the sum of all fractions.

‡Amounts of phosphorus applied in mg P kg⁻¹ soil.

§The sparingly available P did not exist based on the criteria of this study.

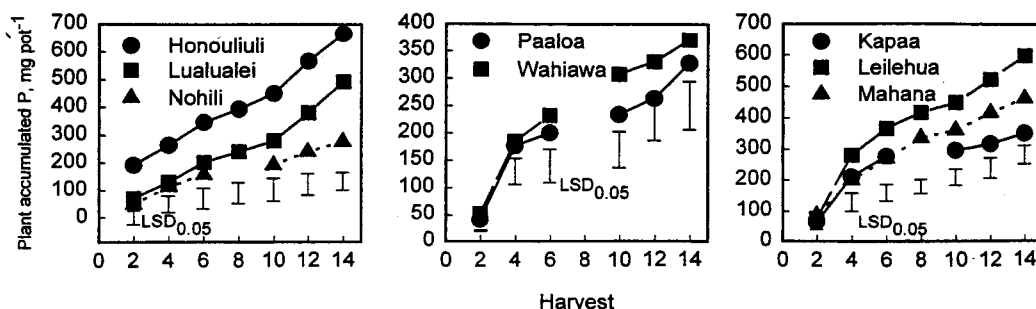


Fig. 6. Accumulated plant P uptake in eight soils under continuous cropping. Phosphorus was added to raise soil solution P to 0.2 mg L^{-1} .

by a much higher readily available pool and lower sparingly available pool in the former than in the latter soil. Accordingly, P applied to the Leilehua had the greatest availability among the three high P sorption soils. Greenhouse plant P uptake results confirmed the above ranking in P availability (Fig. 6), indicating some promise of grouping soil P into pools for improved P management.

CONCLUSIONS

Eight soils were treated with 4 levels of P and fractionated with a modified sequential extraction method. Availability of the 7 P fractions was evaluated by a 14-crop greenhouse exhaustion experiment. The 7 fractions were then grouped into 3 discrete pools according to plant availability.

In the slightly weathered soils, four fractions, Strip P, $\text{NaHCO}_3\text{-P}_i$, HCl-P and residual P, contributed the most to plant available P. Strip-P and $\text{NaHCO}_3\text{-P}_i$ seemed to have similar availability until extractable P by these extractants declined to a certain level. Subsequent plant P withdrawal did not lower Strip P much further, suggesting that a buffer exists to replenish the Strip P. The pools buffering strip P appeared to be the $\text{NaHCO}_3\text{-P}_i$, HCl-P , and residual P. The decline in HCl-P and residual P was significantly correlated with accumulated plant P, which differed from that in the highly weathered soils.

In the highly weathered soils, Strip-P and $\text{NaHCO}_3\text{-P}_i$ and NaOH-P_i appeared to be responsive to plant removal of available soil P. As in the slightly weathered soils, Strip P and $\text{NaHCO}_3\text{-P}_i$ were the first fractions removed by plants, but their relative contributions to plant available P could not be resolved. The NaOH-P_i appeared to be significant in buffering available P

supply in all the highly weathered soils. The residual P was not available, which differed from that in the slightly weathered soils.

An attempt was made to partition soil P into 3 pools, readily available, reversibly available, and sparingly available. In the slightly weathered soils, the readily available pool included the Strip P and the $\text{NaHCO}_3\text{-P}_i$. The reversibly available P consisted of the remaining P fractions. No sparingly available P was found in the slightly weathered soils. In the highly weathered soils, the readily available pool also consisted of both the Strip P and the $\text{NaHCO}_3\text{-P}_i$. NaOH-P_i , organic P ($\text{NaHCO}_3\text{-}$ and NaOH-P_o), and HCl-P were considered reversibly available. The residual P was considered sparingly available P, because it not only failed to respond to plant removal of soil P, but also continued to accumulate while plants were removing P.

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